Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28194

263 (2022) 3–8
July

Levelized cost analysis for desalination using renewable energy in GCC

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Received 28 February 2022; Accepted 12 April 2022

ABSTRACT

Seawater desalination plants are considered the main source of fresh water in most of the GCC countries. Desalination is an energy-intensive process, where energy price represents more than 44% of the cost of desalinated water. Almost all commercial desalination plants rely on fossil fuel to secure the energy requirements either in thermal or electrical form. GCC countries are gifted with consistent and predictable solar energy that can be used to power the desalination processes and to improve their sustainability and to reduce their environmental impacts. Solar energy can be harvested using photovoltaics (PV) panels or different forms of concentrated solar power. In this paper, the energy cost in the form of levelized cost of energy (LCOE) was calculated for a PV solar energy generation plant and hence, the levelized cost of water (LCOW) for a reverse osmosis reference desalination plant in the six GCC countries had been estimated and compared. System Advisor Model (SAM) is a comprehensive renewable energy analysis software developed by the National Renewable Energy Laboratory and is used in this work. SAM relies on the metrological weather data for the evaluation of solar energy. The included financial model within SAM was used to estimate the LCOE and the Power Purchase Agreement price. A reference reverse osmosis desalination plant of a capacity of 400,000 m^3/d (88 MIGD) has been used in this study. The power consumption of the plant is estimated as 76 MW at 4.56 kWh/m^3. A photovoltaic power plant of capacity 76 MW was designed and the LCOE produced by this pant was estimated. The LCOE was different according to the PV plant location in GCC countries. The obtained LCOE is used to estimate the LCOW produced by this plant using Desalination Economic Evaluation Program software. The LCOE for the studied locations ranged from 8.46 to 9.11 ¢/kWh (1.0 USD $ = 100 ¢), and the LCOW ranged from 103.0 to 105.0 ¢/m^3, compared to 10.737 ¢/kWh and 110.1 ¢/m^3 for the conventional combined cycle power plant.

Keywords: Levelized cost of energy (LCOE); Levelized cost of water (LCOW); Desalination processes; Renewable energy; Solar desalination; System Advisor Model (SAM); Desalination Economic Evaluation Program (DEEP)

1. Introduction

Renewable energy can play a vital role in desalination. Renewable technologies suited to desalination include solar thermal, solar photovoltaics, wind, and geothermal energy [1,2]. Solar technologies based on solar heat concentration, notably concentrating solar power, produce a large amount of heat and is suited to thermal desalination. Photovoltaic (PV) and wind electricity are often combined with membrane desalination units (reverse osmosis, electrodialysis). As electricity storage is still a challenge, combining power generation and water desalination can be a cost-effective storage option when generation exceeds demand.

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

Renewable energy-based desalination provides a sustainable way for freshwater production. In the past decade, the cost of renewable desalination was higher than that of conventional desalination based on fossil fuels for energy input [1,2]. However, solar desalination is expected to become economically attractive as renewable technologies' costs continue to decline, and the prices of fossil fuels continue to increase. Using locally available renewable energy resources for desalination is likely to be a cost-effective solution, particularly in remote regions, with low population density and inadequate infrastructure for fresh water and electricity transmission and distribution [3].

2. Methodology

The key factor for utilizing renewable energy sources in desalination is the overall cost of freshwater production. The levelized cost of water (LCOW) represents the average cost for water production over the project life. The energy cost is presented by the levelized cost of energy (LCOE) and is used in the calculation of the energy cost in water. In this work, a reference desalination plant was selected for this investigation, as shown in Table 1. This plant was mainly operated using combined cycle power plants (CCPP). The LCOW of this plant is first evaluated based on the energy produced by CCPP. The required power for this desalination plant was estimated and then provided by a renewable energy power plant (REPP). The LCOE of these REPP was evaluated based on the latest cost of renewable energy equipment. The LCOE of the REPP is then used to estimate the LCOW based on renewable energy. Renewable energy sources are particularly site-dependent, and for this reason, the study includes an investigation of REPP in different GCC countries; Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, the United Arab Emirates, for comparison, Fig. 1.

The power needed for this desalination plant was estimated using the average specific energy consumption according to the technology type and plant capacity, among other parameters. The Desalination Economic Evaluation Program (DEEP) 5.13 software [5,6] was used to estimate the power and the LCOW based on the CCPP. DEEP estimates the LCOE of the combined cycle and uses this value to evaluate the LCOW. The combined gas-steam cycle was used with oil as the fuel. However, the LCOE using REPP is calculated and plugged into DEEP to evaluate the LCOW using renewable energy. System Advisor Model (SAM) software [7–9] was used to evaluate the LCOE of the REPP. SAM uses design DNI value from the weather data file along with other design parameter values to determine the nominal capacities of the solar field and other components in the system. The design DNI is different from the hourly DNI values in the weather file. The design DNI is used to calculate the nameplate capacities. For the reference reverse osmosis

Table 1
Reference desalination plants [4]

	Shuaiba-4
Status	Construction
Location	Shuaiba, Saudi Arabia
Location type	Land-based
Technology	Reverse osmosis
No. of passes	Two-pass
Pretreatment	Dual media filtration
No. of units	
Max. brine temp.	Atm. temp.
Feedwater type	Seawater
Capacity	400,000 m^3/d
Online date	2020
Award date	2017
User category	Municipalities
Est. EPC cost	SAR 1,600,000,000
Est. project cost	

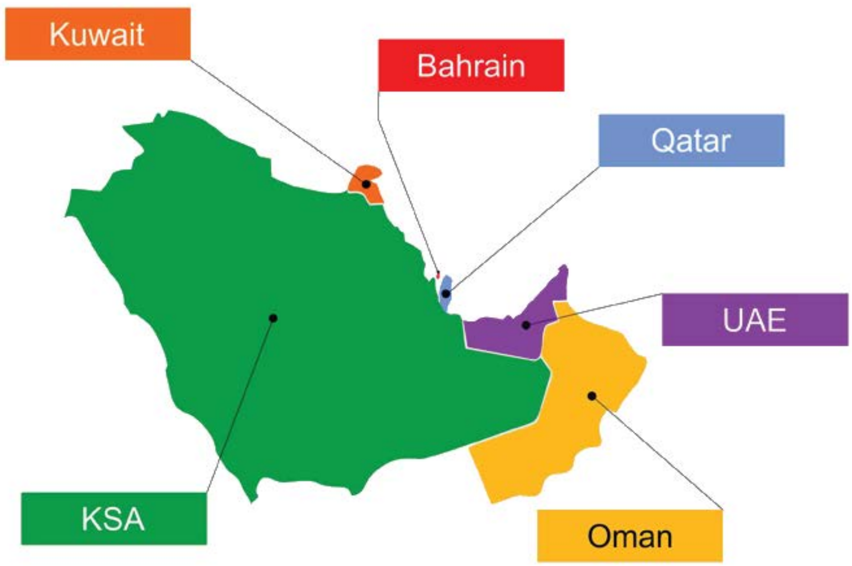

Fig. 1. GCC countries.

desalination plant, the required electric power is 76 MW. A photovoltaic power plant (PVPP) of capacity 76 MW was designed, and the LCOE is evaluated using SAM software as explained above.

3. Photovoltaic power plant economics

A 76 MW, net output capacity PVPP was designed using SAM 2020.11.29 software. The design steps started with choosing the PVPP location and specifying the weather data file. In this study, we downloaded the required weather data files from OneBuilding [10]. Details presented here are for PVPP using weather data obtained from Kuwait International Airport. The next step in the design procedure was to select the PV module and inverter. SunPower SPR-E19-310-COM PV panels were selected for this plant. The module's nominal efficiency was 19%, and the maximum DC power produced based on the reference conditions of 1,000 W/m^2 and PV cell temperature of 25°C was 310 W_{dc}. Other specifications of the module, along with the characteristics curve, are shown in Fig. 2.

A Power Electronics FS0450PU inverter was selected for this system; specifications and characteristics of the inverter is shown in Fig. 3. The next step was to size the system based on the needed capacity. SAM provides two methods for sizing the system, and we chose the automated estimation of the system configuration method.

For the case of Kuwait International Airport data, the following system sizing results were obtained from SAM.

Nameplate DC capacity: 91,198 kW_{dc}
Total AC capacity: 76,050 kW_{ac}
Total inverter DC capacity: 78,826 kW_{dc}
Number of modules: 294,048
Number of strings: 24,504
Total module area: 479,592 m^2
String V_{oc} at reference conditions (V): 772.8
String V_{mp} at reference conditions (V): 656.4

The next step was to estimate the system cost. The cost of the modules and inverters, along with the balance of system (BOS) equipment, are evaluated from ATB [11], and supplied into SAM, Fig. 4. The total direct capital cost was 78,522,072 $.

The indirect capital cost includes the permitting and environmental studies, engineering, and development overhead

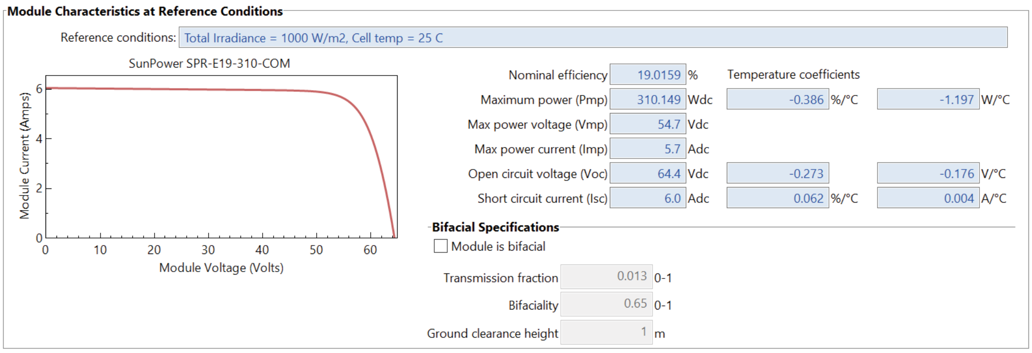

Fig. 2. SunPower PV module characteristics.

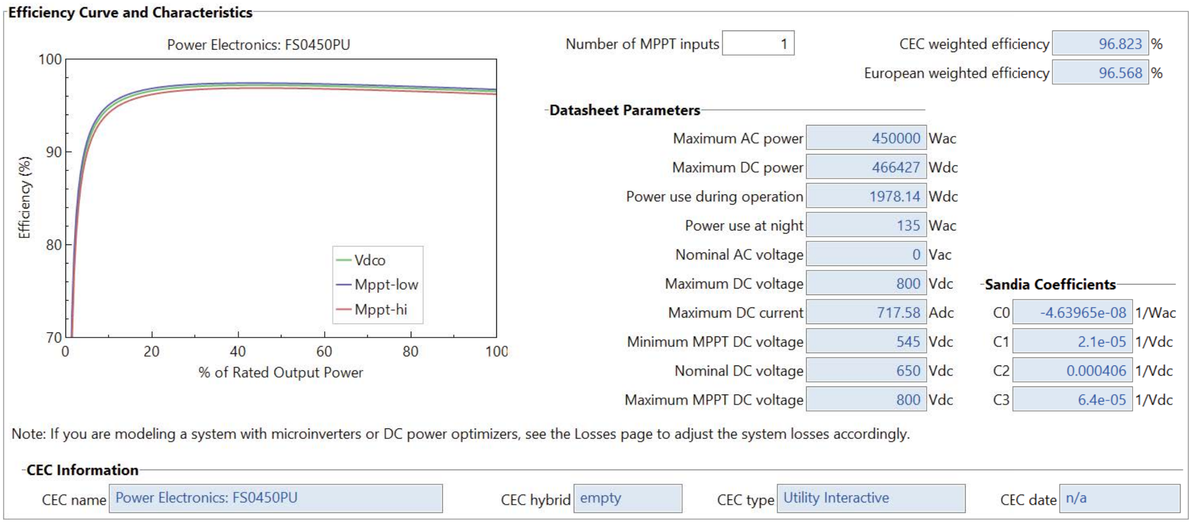

Fig. 3. Power electronics inverter characteristics.

along with the land cost, as shown in Fig. 5. It is worth mentioning that the sales tax is omitted in this study as it is not applied in many GCC countries.

For the PVPP in Kuwait, the total indirect cost was estimated to be 15,503,777 $, which results in a total installation cost equal to 94,025,848 $, and the cost per kW of the capacity was 1,133.0 $/kW. The project was financed by a loan for 60% of the cost of the total installed capacity, with an inflation rate of 2.5%/y and discount rate of 10%/y, project lifetime of 25 y, and no taxes. The LCOE of this plant was estimated at 9.045 ¢/kWh. For the private sector to be involved in these projects, the electricity was usually sold to the national grid authority according to a Power Purchase Agreement (PPA) price. For an internal rate of return (IRR) of 11% at the 20th year, the PPA was estimated to 9.102 ¢/kWh. This was the value that has been used in the evaluation of the LCOW using DEEP software. Table 2 shows a summary of the results obtained by SAM for the PVPP in different locations in GCC countries.

In Table 2, the real levelized cost is a constant dollar, inflation-adjusted value, while the nominal LCOE is a current dollar value, the same definition for the real and nominal PPA prices is applied [7]. LCOE is the total value of energy costs divided by the total energy generated. For the evaluation of the LCOW, the nominal PPA prices were used. The net present value (NPV) in Table 2 represents the time value of money and a discount rate for the cash flows, while the IRR is the discount rate that causes the NPV of electricity investments to become zero [12].

The values of the nominal PPA prices from Table 2 were used to calculate the LCOW using DEEP software, Table 3. For the conventional CCPP, the LCOE were estimated at 10.737 ¢/kWh, which was resulted in an LCOW of 1.1014 $/m^3, which was higher than all the values in Table 3.

Kuwait International Airport was not the optimum location for a PVPP. Two further sites in Kuwait were also studied for choosing better location; results are shown in Table 4. The LCOW for the three sites in Kuwait were also shown in Table 4. The Salmi site showed minimum freshwater cost. It is worth mentioning that, the Kuwait Institute for Scientific Research (KISR) built the first renewable energy park in Kuwait in Shagaya, near Salmi.

4. Conclusions

Renewable energy is a sustainable source for supplying energy for desalination. Like most renewable power generation technologies, PV systems are capital intensive but have no fuel costs. The LCOE for the studied locations ranged from 8.46 to 9.11 ¢/kWh, and the LCOW ranged from

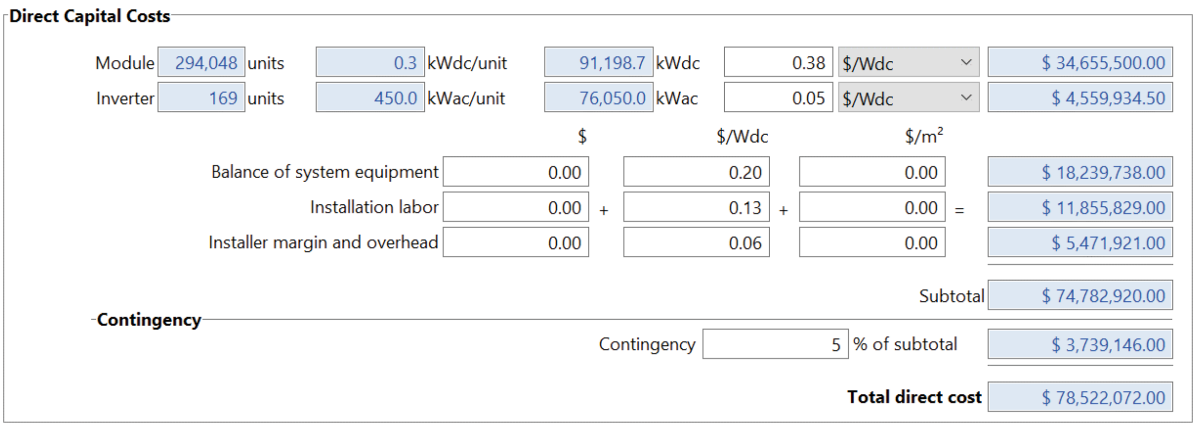

Fig. 4. Direct capital cost of PVPP in Kuwait.

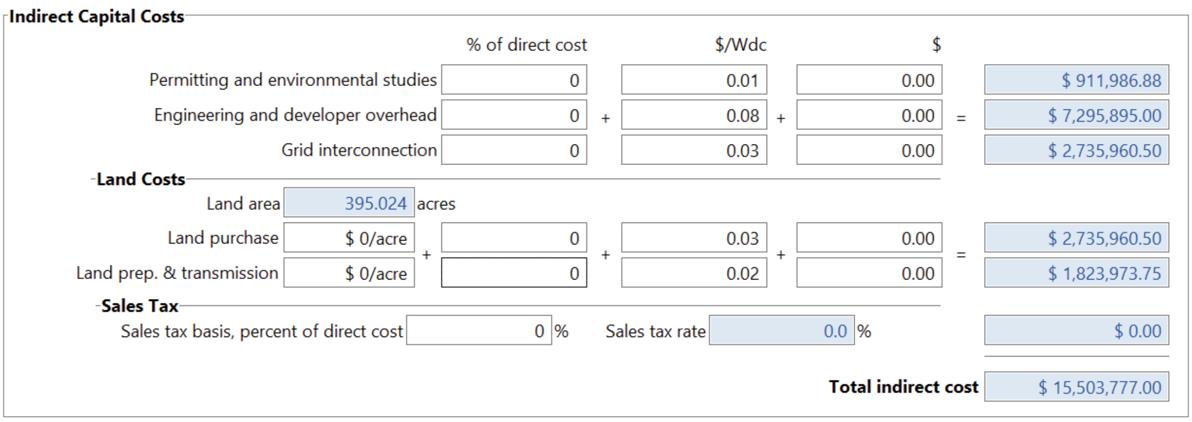

Fig. 5. Indirect capital cost of the PVPP in Kuwait.

Table 2
PVPP analysis results in GCC countries

Country	BHR	KWT	OMN	QAT	SAU	ARE
Location	Bahrain Intl Ap	Kuwait Intl Ap	Muscat Intl Ap	Doha Intl Ap	Riyadh Khalid Intl Ap	Abu Dhabi Intl Ap
Annual energy, GWh/y	173.040	169.449	170.985	175.046	173.154	176.449
Annual energy yield, kWh/kW	1,897.401	1,858.018	1,874.861	1,919.395	1,898.641	1,934.775
Capacity factor	21.660	21.210	21.403	21.911	21.674	22.086
Performance ratio, %	0.781	0.770	0.769	0.770	0.765	0.769
No of modules	294,048	294,048	294,048	294,048	294,048	294,048
No of inverters	169	169	169	169	169	169
Installation cost, $	103,343,968	103,342,432	103,346,832	103,345,840	103,343,800	103,345,784
Installation cost, $/kW	1,133	1,133	1,133	1,133	1,133	1,133
Size of debt, $	79,833,544	79,833,256	79,833,752	79,833,696	79,833,536	79,833,672
Size of equity, $	23,510,428	23,509,178	23,513,082	23,512,144	23,510,264	23,512,112
PPA price (year 1), ¢/kWh	8.354	8.529	8.459	8.261	8.348	8.195
PPA price (nominal), ¢/kWh	8.915	9.102	9.027	8.816	8.909	8.746
PPA price (real), ¢/kWh	7.353	7.507	7.445	7.271	7.348	7.213
LCOE (nominal), ¢/kWh	8.860	9.045	8.971	8.762	8.854	8.692
LCOE (real), ¢/kWh	7.307	7.460	7.399	7.226	7.302	7.169
Project NPV, $	690,553	691,413	689,471	689,799	690,597	689,875
NPV for PPA revenue, $	111,404,128	111,401,488	111,408,680	111,407,336	111,403,976	111,407,200
IRR target year	20	20	20	20	20	20
IRR in target year, %	11.00	11.00	11.00	11.00	11.00	11.00
IRR at end of project, %	13.07	13.07	13.07	13.07	13.07	13.07

Table 3
LCOW produced in different GCC countries

Country	BHR	KWT	OMN	QAT	SAU	ARE
Location	Bahrain Intl Ap	Kuwait Intl Ap	Muscat Intl Ap	Doha Intl Ap	Khalid Intl Ap	Abu Dhabi Intl Ap
PPA nom, ¢/kWh	8.915	9.102	9.027	8.816	8.909	8.746
LCOW, $/m^3	1.0427	1.0488	1.0463	1.0395	1.0427	1.0373

1.03 to1.05 $/m^3, compared to 10.737 ¢/kWh and 1.101 $/m^3 for the conventional CCPP.

The three key drivers of the LCOE of PVPP are:

- The capital and the installation costs of PV modules and BOS ($/W);
- The average annual electricity yield (kWh per kW); functions of the local solar radiation and the solar cells' technical performance;
- The finance cost of the PV system.

While desalination processes are still costly, declining renewable energy technology deployment costs are expected to bring the desalination cost down in the coming years, which is of particular interest to remote regions and

Table 4
PVPP and LCOW in three different locations in Kuwait

Country	KWT	KWT	KWT
Location	Kuwait Intl Ap	Failaka Island	Salmi
Annual energy, GWh/y	169.449	176.081	182.421
Annual energy yield, kWh/kW	1,858.018	1,930.740	2,000.264
Capacity factor	21.210	22.040	22.834
Performance ratio, %	0.770	0.778	0.779
No of modules	294,048	294,048	294,048
No of inverters	169	169	169
Installation cost, $	103,342,432	103,342,944	103,341,784
Installation cost, $/kW	1,133	1,133	1,133
Size of debt, $	79,833,256	79,833,456	79,833,280
Size of equity, $	23,509,178	23,509,488	23,508,502
PPA price (year 1), ¢/kWh	8.529	8.208	7.921
PPA price (nominal), ¢/kWh	9.102	8.760	8.454
PPA price (real), ¢/kWh	7.507	7.225	6.972
LCOE (nominal), ¢/kWh	9.045	8.706	8.401
LCOE (real), ¢/kWh	7.460	7.180	6.929
Project NPV, $	691,413	690,915	691,561
NPV for PPA revenue, $	111,401,488	111,402,888	111,400,896
IRR target year	20	20	20
IRR in target year, %	11.00	11.00	11.00
IRR at end of Project, %	13.07	13.07	13.07
LCOW, $/m^3	1.0488	1.0379	1.0279

islands with small populations and for areas of inadequate infrastructure for freshwater and electricity transmission and distribution.

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